WIDELY TUNABLE LASER ON PHOTONIC CRYSTAL

This invention relates to the field of tunable laser structures.

At present, laser diodes are used as tunable sources within the framework of optical data transmission applications. In this context it is important to achieve high tunability, i.e. a wide wavelength range of laser emission without the danger of mode-hopping which adversely affects the quality of optical transmission.

Several types of tunable lasers are known, including lasers that are called distributed reflector lasers, commonly called DRB (Distributed Bragg Reflector) lasers. This "standard" tunable laser is shown in Figure 1.

It is a monolithic semiconductor component typically composed of an amplifying section 1, called the "active" section, coupled to a tuning section, called the "Bragg" section 2. Optionally, a section called the "phase" section 3 can be located between the active section 1 and the Bragg section 2.

The active section 1 has a vertical structure that is classically composed of an active amplification layer CA, which is located between two cover layers 4, 5 with opposite doping. This active layer CA is conventionally composed of a succession of quantum wells separated by layers that form potential barriers. Upper 6 and lower 7 electrodes allow injection of current I_a through these layers in order to produce an optical amplification effect.

The Bragg section 2 is a reflecting section with a peak reflectivity for at least one value of the reflection wavelength. One of its ends is thus coupled to the active section 1. It has a vertical structure composed of a homogeneous guiding layer CG (called "massive" or "bulk" in English), which is located between two cover layers 4, 5. Moreover, a grating 8 is located in one of the cover layers in the vicinity of the guiding

layer and, along the guide, forms a periodic alternation of materials with different refractive indices. This grating 8 is intended to comprise a wavelength-selective reflector with at least one main reflectivity peak, i.e. a maximum reflection wavelength. This wavelength, called the "Bragg" wavelength λ_{Br}, is determined by the pitch of the grating Λ and the effective refractive index n_b of the guiding layer CG, according to the classical formula $\lambda_B = 2\Lambda.n_b$.

The external face 9 of the active section 1 comprises a reflector that is not selective for wavelength and with the Bragg section 2 forms a Fabry-Perot resonant cavity which contains the active section 1.

According to a first type of laser, the laser power generated in the cavity is extracted essentially by this external face 9, which is then called the "front face". It is made semi-reflective by means of a suitable antireflection layer. Ordinarily its reflectivity is roughly from 1.5 to 5% in order to allow at the same time laser oscillation and emission of the generated laser wave to the exterior of the component. The end of the Bragg section that is not coupled to the active section comprises a second external face 10 of the component, called the "rear face"; and to prevent formation of parasitic modes, it is made highly antireflective.

According to another type of laser, the laser power generated in the cavity can be extracted essentially by the end of the Bragg section that is not coupled to the active section. This end then becomes a front face or is coupled to other sections that are integrated into the component, such as the photodetector, amplifier, or modulator. In this case, the external face 9 of the active section 1 becomes a rear face that can be highly reflective, ordinarily with reflectivity exceeding 90%.

In all cases, laser oscillation is possible for a series of longitudinal resonant modes (Fabry-Perot modes) with wavelengths that are dictated by the optical length of the cavity. An oscillation will be produced according to one of these modes in the case of adequate

tuning between its wavelength and the Bragg wavelength λ_B.

To implement a wavelength-tunable source, it is enough to be able to modify the Bragg wavelength λ_B. To do this, the guiding layer CG of the Bragg section must be composed of a material that is transparent over the entire range of operating wavelengths and must have an effective refractive index n_b that can vary as a function of control. The material is for example an active medium selected because its index is a function of the density of the carriers that it contains. The guiding layer CG is then located between the two cover layers 4, 5 with opposite doping, and the Bragg section comprises an upper electrode 11 cooperating with the aforementioned lower electrode 7 in order to allow the injection of an electrical control current I_b into the guiding layer CG.

Thus, by controlling the current I_b the Bragg wavelength λ_B can be adjusted to a value near the wavelength that was selected from that of the Fabry-Perot modes of the cavity, and thus the laser can be induced to oscillate with this selected wavelength.

More precise adjustment of the oscillation wavelength can be done, moreover, by controlling the temperature of the component. By influencing the temperature, the indices of the guiding layers of the cavity can be adjusted, as can its optical length as well; this results in a shift of the comb of wavelengths of the Fabry-Perot modes.

Another approach, which is shown in Figure 1 and which makes it possible to more easily adjust the oscillation wavelength, is to provide an independent phase section 3. As shown in the illustrated example, the phase section 3 lengthens the Bragg section in the direction of the active section 1, with an identical vertical structure, but where the Bragg grating is absent. It also comprises an upper electrode 12 that cooperates with the lower electrode 7 of the component to allow the injection of an electrical current I_p into the guiding layer CG. Thus, by influencing the injected electrical current I_p, the optical length of the cavity is changed; this shifts the comb of wavelengths of the Fabry-Perot modes without affecting the Bragg wavelength λ_B.

The operation of a tunable laser of the type described above will thus be determined by three parameters: the current I_a injected into the active section 1; the current I_b injected into the Bragg section 2; and the current I_p injected into the phase section 3, or, in the absence of the phase section, the temperature.

In practice, laser emission of fixed power and wavelength that can be chosen from a standardized grating is required. For each selectable wavelength, the values of the three parameters I_a, I_b, I_p must moreover be chosen such that single-mode laser operation results. One parameter that is representative of this operation is called the "side mode suppression ratio" (SMSR). The SMSR is defined as the ratio of the power of the primary oscillating mode to that of the secondary oscillating mode of greater power (next to the primary mode). To ensure the desired transmission quality, a minimum value is assigned to this ratio, which is generally expressed in decibels, for example 35 dB.

Figure 2 shows a curve that is representative of the variations of the wavelength λ of the primary oscillating mode of the cavity as a function of the current I_b (expressed in mA) injected into the Bragg section. Since the Bragg wavelength λ_B is a decreasing function of this current I_b, it is confirmed that the wavelength λ decreases when I_b increases. Moreover, mode-hopping is manifested by the discontinuities of the curve. Each selectable wavelength $\lambda_1, \lambda_2, \ldots \lambda_q$ is included between two values of consecutive Bragg wavelengths. For example, the selection of a given mode can be obtained by fixing the Bragg wavelength between two values λ_{B1}, λ_{B2}, which correspond respectively to mode hops that correspond to specific values on the curve, for example I_{b1} and I_{b2} of the Bragg current I_b.

Thus, by causing the control current I_b of the Bragg section to vary, it is possible to choose the laser emission wavelength and accordingly to tune the laser. Ordinarily a DBR laser such as is shown in Figure 1 promises tunability of roughly 15 nm.

To increase the tunability range, it would be possible to place the active section between two Bragg sections, each comprising a wavelength-selective grating. Such a laser, shown in Figure 3, is known as a SG-DBR (Sample Grating-Distributed Bragg Reflector) and has the same structure as a DBR laser such as the one described above, but includes two Bragg sections 2 and 2' which are coupled to each end of the active section 1.

As shown in Figure 4, each Bragg section 2 and 2' will produce a comb of reflection peaks, each peak corresponding to a selectable emission wavelength (Figures 4a and 4b). In the case of a SG-DBR laser, one of the peaks of the first Bragg section 2 will coincide with a peak of the second Bragg section 2', and a laser oscillation will be produced for the Fabry-Perot mode with a wavelength that is nearest the coincidence peak (Figure 4c). Current control of one of the Bragg sections 2, 2' shifts one of the combs and causes the emission wavelength of the laser to vary by the Vernier effect. Classically, a SG-DBR laser, such as is shown in Figure 3, promises tunability of roughly 40 nm.

A SG-DBR laser offers a tunability range which is interesting, but limited by the shape of the envelope of reflection peaks, which is especially a cardinal sine.
This shape of the envelope of the reflection peaks has the result that the power emitted by the tunable laser is not constant according to the selected transmission mode.

Figure 5 schematically shows a DBR laser such as was described above, integrated with an electro-absorption modulator, ordinarily called an ITLM (Integrated Tunable Laser Modulator in English). Such a component is used primarily in wavelength division multiplexing (WDM).

An ITLM component includes, beside the amplifier section 1 and the tuning section 2 of the laser, a modulation section 21. The modulation section 21 has a vertical structure classically composed of an active absorbing layer CA', for example composed of quantum wells or a bulk material. The wavelength corresponding to the

photoluminescence peak of this layer CA' is roughly 50 nm lower than the laser emission wavelength. The modulation section 21 likewise includes an upper electrode cooperating with a lower electrode to allow application of a control voltage to the absorbing layer CA' in order to cause the absorption coefficient of the optical signal to vary and amplitude modulation to be produced.

The output power of a classic ITLM component is, however, limited by the strong reflection of the tuning section 2. In fact, the tuning section is relatively long (typically exceeding 250 microns) in order to allow good frequency selectivity and to guarantee a good SMSR, such as defined above. However, this entails a power reflection coefficient in the tuning section that is relatively high, roughly 0.3 dB.

Moreover, the output power of a classic ITLM component is not constant as a function of the selected laser transmission mode.

The object of this invention is to suggest a laser structure which has an enlarged tunability range with slight variation of the power over the entire tunability range.

To do this, the invention suggests replacing the Bragg gratings of the tuning sections of the laser by reflectors composed of specific photonic crystals. The invention also has the advantage of a simplified production process, because only a single epitaxy stage is necessary.

More specifically, this invention relates to a semiconductor laser structure comprising a light guiding core located between a lower confinement layer and an upper confinement layer comprising an engraved ribbon guide loading the core to form an optical guide, the guiding core comprising an amplifier section delineated by two reflectors forming a resonant cavity that allows selection of a laser mode with a tunable wavelength, characterized in that at least one reflector is composed of a photonic crystal section comprised of pairs of gratings of holes that are located on either side of the ribbon

guide, each grating of holes of the photonic crystal section having holes arranged in a trapezoid, the larger base of the trapezoid being farther away from the ribbon guide than the smaller base.

According to one characteristic, the reflector comprised of a photonic crystal section is composed of sampled pairs of gratings of holes located on either side of the ribbon guide.

According to one characteristic, the sampling of the pairs of gratings of holes is constant.

According to one embodiment, the two reflectors are composed of a photonic crystal section comprised of sampled pairs of gratings of holes, the sampling of the pairs of gratings of holes of each photonic crystal section being different.

According to the embodiments, the pitch of the gratings of holes is constant or variable.

According to one application, the structure as claimed in the invention comprises moreover a modulation section, the reflector located between the amplifier section, and the modulation section being composed of a photonic crystal section comprised of at least one pair of gratings of holes that are located on either side of the ribbon guide.

The specifics and advantages of this invention will become clearer by reading the following description given by way of a non-limiting example, with reference to the attached figures.

- Figure 1, already described, is a diagram of a DBR tunable laser known from the prior art;

- Figure 2, already described, is a curve illustrating the variations of the emission wavelength of the laser from Figure 1 as a function of the current injected into the Bragg section;

- Figure 3, already described, is a diagram of a SG-DBR tunable laser known from the prior art;

- Figures 4a to 4c, already described, illustrate the operating principle of emission of the laser from Figure 3;

- Figure 5, already described, is a diagram of an integrated laser-modulator ITLM known from the prior art;

- Figure 6 is a diagram of a photonic crystal single-mode laser known from the prior art;

- Figure 7 is a diagram of a tunable laser as claimed in the invention;

- Figures 8a to 8c illustrate different embodiments of the photonic crystal sections of the laser from Figure 7;

- Figure 9 is a diagram of a tunable laser integrated into a modulator as claimed in the invention;

- Figures 10a to 10c illustrate the operating principle of emission of a laser as claimed in the invention.

A tunable laser is implemented as claimed in the invention. Tunability of the laser is obtained classically by choosing a Fabry-Perot mode in a laser cavity defined by an active section encompassed by two reflectors, of which at least one is selective for

wavelength. As claimed in the invention, at least one reflector is composed of specific photonic crystals.

The idea of a photonic crystal, or photonic band gap optical component (*bande interdite photonique*, or BIP), is a recent development. The first component of this type was built by Eli Yablonovitch in 1991. Typically this component is composed of a bulk dielectric material, for example III-V semiconductor, including a distribution of regularly spaced structures, called "holes". The holes are generally composed of air, but can be composed of another dielectric material, different from the bulk material, with a refractive index less than that of the bulk material. In a three-dimensional photonic component, the structures or holes generally have the shape of balls, and in a two-dimensional photonic component the structures generally have the shape of cylinders.

The regular arrangement of the holes in the bulk material makes it possible to liken such a component to a crystal, called a photonic crystal. This periodic structure entails the formation of one or more photonic band gaps encompassed by allowed energy bands in a manner analogous to the electronic structure of a semiconductor crystal.

In a photonic component, the position of the photonic band gap is determined by the spacing between the holes, i.e. the pitch, and the width of this photonic band is closely linked to the filling rates of the holes in the bulk material (known as air filling in English terminology), i.e. it depends on the diameter of said holes. Thus it is possible to make a photonic optical component which is completely reflective in a given spectral band.

Photonic components are the subject of many applications and experiments for transmission, emission or detection of optical signals. In particular, they represent more or less perfect filters.

Thus, making a laser structure using photonic crystals as a Fabry-Perot cavity reflector has been considered. The publication "Single mode operation of 2D photonic

crystal based short coupled cavities lasers", Applied Physics Letters, Vol. 79, No. 25, pp. 4091-4093, 2001, describes a laser structure with a cavity that is delineated by "photonic" mirrors. Such a structure is shown in Figure 6.

A ribbon optical guide structure, known as a "ridge waveguide" in English, is implemented. This structure includes an optical light guiding core 13, which is composed of an amplifier material and which is located between two cover layers 14, 15. The ribbon 16 is made in the upper cover layer 14 to load the core 13 and to form an optical waveguide.

The structure described in this publication includes a double laser cavity delineated on one side by a highly reflective rear mirror 17 composed of a grating of holes forming a photonic crystal and on the other side by a split facet 9, and by an internal mirror 18 comprised of one photonic crystal section that is composed of a pair of gratings of holes that are arranged laterally on either side of the ribbon guide 16.

The laser structure defined in this way emits a single mode due to the coupling of the two laser cavities defined above.

As claimed in the invention, a tunable laser structure is implemented that comprises at least one wavelength-selective reflector and at least one reflector composed of a photonic crystal section, said photonic section being able to comprise said wavelength-selective reflector. This structure is shown schematically in Figure 7.

The laser structure as claimed in the invention is a semiconductor component comprising an optical light guiding core 13 located between two cover layers 14, 15 with opposite doping. The optical core 13 has an amplifier section called the active section 1, coupled to at least one passive section that comprises a wavelength-selective reflector, called the tuning section 2. The optical core is composed of an amplifier material CA on the active section 1 and a homogeneous material CG on the tuning section or sections 2.

A ribbon 16 is moreover engraved on the upper cover layer 14 to load the core 13 and to form an optical waveguide, known in English as a "ridge waveguide". The upper electrodes are located above each section and cooperate with a lower electrode in accordance with what was described with reference to the prior art.

At least one reflector is composed of a photonic crystal section that is comprised of at least one pair of gratings of holes 19. The holes of each grating 19 extend through the upper cover layer 14 and the guiding layer 13 as far as into the lower cover layer 15. The gratings of holes 19 of each pair are located respectively on either side of the ribbon guide 16.

As claimed in the invention and as shown in Figures 8a to 8c, each grating of holes 19 of the photonic crystal section has a trapezoidal arrangement of holes, the larger base of the trapezoid being farther away from the ribbon guide 16 than the smaller base. According to one version, the trapezoidal arrangement can be a triangle.

Several configurations are conceivable for the arrangement of the gratings of holes 19 and depend on the chosen grating (triangular, square, or other), on the pitch, and on the order of diffraction of the grating.

The pitch of each grating can be constant or variable, depending on the application.

According to one advantageous characteristic, it is the reflector of the tuning section that is composed of a photonic crystal section. The pairs of gratings of holes 19 are then sampled. This arrangement, which means that the reflector has several reflection peaks, allows an enhanced tunability range. Moreover, in the case in which the two tuning sections 2, 2' would be formed on either side of the active section 1, the sampling is not identical on the two sections.

Advantageously, the laser structure as claimed in the invention can comprise two tuning sections 2, 2'. Each tuning section 2, 2', which is composed of sampled photonic crystals, forms a comb of reflection peaks according to the same principle as the Bragg sections of the lasers described above. In fact, each grating of holes 19 will create local periodic modulation of the index, and sampling of said gratings of holes 19 by pairs on either side of the ribbon guide 16 will yield modulation on a scale of roughly several hundred microns.

As shown in Figures 10, the envelope of the transmission comb of the tuning sections as claimed in the invention is much more flat, due to the appropriate arrangement of the holes in each grating 19 in a trapezoid such as described above. This arrangement of holes makes it possible to obtain a more or less uniform comb of reflection peaks. For this reason, the tunability range is enlarged and the power variations according to the emission wavelengths are reduced.

Figure 9 shows one application of the invention to ITLM components in the area of a source integrating a tunable laser and an electro-absorption modulator.

The laser structure as claimed in the invention, such as was described above, then moreover includes a modulation section 21. The reflector, which is located between the amplifier section 1 and the modulation section 21, is advantageously comprised of a photonic crystal section composed of at least one pair of gratings of holes 19 that are located on either side of the ribbon guide 16. This photonic crystal section forms an optical cavity with the tuning section 2, which can be composed of a classic Bragg grating 8 or a photonic crystal section composed of pairs of gratings of holes, such as were defined above.

The tuning section 2 must be long enough (typically exceeding 250 microns) to allow good mode selectivity, whereas the gratings of holes extend only over a very short length (a few microns to a few dozen microns). The trapezoidal arrangement of the

grating of holes in particular makes it possible to ensure a low reflection coefficient (roughly a few percent) that varies little with the selected wavelength. It is thus possible to obtain a high power ITLM component that emits over a wide range of frequency tunability. In principle, in this application, the gratings of holes do not have to be sampled.